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AN ANALYSIS OF RF DEFLECTORS

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We wish to consider the type of deflector appropriate for a high-energy, spatially-separated particle beam in Area 1. The goal we set for ourselves is a beam which will separate K-mesons from π-mesons and protons at as high a momentum as practical with a purity comparable to that of present high quality RF beams. The beam should have a length comparable to the neutrino beam in area 1 (about 900 m). It should have as large a solid angle acceptance as is possible, and hence would be able to satisfy the demands of counter experiments consistent with the duty cycle of the separators, as well as bubble chamber needs.

We wish to compare three different types of deflectors which might be appropriate for such a beam. The first type is a normal iris loaded waveguide; the second type is a superconducting iris loaded waveguide; and the third type is a dielectric loaded rectangular waveguide which has recently been developed by the Argonne group[1] and considered in the 1969 Aspen Summer Study[2].

Beam Length and Choice of Frequency

Figure 1 is a plot of the drift distance that is required

for K-meson separation from a background of pions and protons as a function of momentum for three different frequencies. This is the distance required for a phase slip between the pions and protons of 2π. For simplicity we here assume we are dealing with a two deflector beam. An rf beam in area 1 is constrained to be approximately 900 m long to be compatible with the neutrino beam presently planned. This means that the maximum deflector separation is about 600 m. At S-band this implies an upper limit for K separation of about 50 GeV/c. While much useful work could still be done at this energy it is not an energy range unique to our machine. Clearly one would like to go to higher energies. An X-band (10 GHz) deflector would extend this to about 92 GeV/c. We thus restrict ourselves to a comparison of our three deflector types at X-band.

In SS-105, a very long (approximately 31 m) dielectric loaded waveguide was proposed as an effective separator at intermediate energies (30-50 GeV/c). With a structure of this length, we must consider placing it in a quadrupole channel in order to give it a reasonable solid angle acceptance. This structure certainly has fabrication problems as well as the complicating feature that a phase change of π is required whenever an optical cross over point occurs. Although this arrangement has certain appealing features we feel we must disregard it at the present since it involves engineering problems which have not been solved. We will thus only consider these three types of structures operating as 'point' deflectors. By a 'point' deflector we here mean

a structure in which we do not make use of the phase slippage of the wanted and unwanted particles that are developed as they traverse the structure itself.

Aperture

The X-band dielectric loaded structure[2] has a useful aperture of 1 x 1 cm. The aperture, a, of an iris loaded structure is given in terms of the wavelength (λ = 3.0 cm at 10 GHz)

$$a \simeq 0.4\ \lambda$$

$$\simeq 1.2 \text{ cm}$$

In the traditional analysis of an iris loaded structure, one considers the 'inscribed square' whose side is given by $a/\sqrt{2}$ = 0.85 cm. We thus see that the dielectric and iris loaded structures have similar apertures to within about 15%. For comparison purposes we will assume a useful aperture of 1 cm for both types of structures.

Solid Angle Acceptance

We assume that the side of the inscribed square for each of these structures is given by 2s and that the deflector has length ℓ. Figure 2a shows the acceptance plot of such a structure. We now consider only the area within the diamond which is shown in Figure 2b. We assume we will do our deflection in a vertical plane. Let the vertical angular acceptance at the target be given α_v (this is the 1/2 angle) and the angular deflection of the separator be given by α_D. Also assume that the vertical magnification from the target to the first deflector is given by m_v and the target 1/2 height is given by t_v.

The natural angular divergence in the first deflector will be given by α_v/m_v.

A more convenient way to parameterize the deflector is in terms of its deflection relative to the natural angular divergence of the beam. Thus we define a quantity η

$$\eta = \frac{\alpha_D m_v}{\alpha_v}$$

Present high quality rf beams operate with η approximately 1. The conditions under which the deflector is optimally filled can now be derived from Figure 2b. The dashed rectangle in Figure 2b represents the undeflected beam in the first deflector. After a deflection of $2\eta\alpha_v/m_v$ (each of our two deflectors contribute) we will bring our wanted particles to the edge of the deflector aperture. For the deflector to be filled we must satisfy the relation

$$(1 + 2\eta)\ \frac{\alpha_v}{m_v} = \frac{s}{\ell}\left(1 - \frac{m_v t_v}{s}\right)$$

We can solve this for α_v

$$\alpha_v = \frac{\alpha_D}{t_v \eta}\left\{s - \ell\alpha_D\left(2 + \frac{1}{\eta}\right)\right\}$$

We can do a similar analysis in the horizontal plane where we may write

$$\frac{\alpha_H}{m_H} = \frac{s}{\ell}\left(1 - \frac{m_H t_H}{s}\right)$$

where the subscript H refers to the corresponding quantities in the horizontal or non-separation plane. We can solve for

α_H

$$\alpha_H = \frac{m_H s}{\ell} - \frac{m^2_H t_H}{\ell}$$

We can maximize α_H with respect to m_H which gives us the relation

$$m_H\Big|_{max} = \frac{s}{2t_H}$$

Inserting this optimum value of m_H into the expression for α_H and dropping the subscript max

$$\alpha_H = \frac{s^2}{4t_H\ell}$$

The solid angle acceptance at the target is given by

$$\Omega = \pi\alpha_v\alpha_H$$

$$\Omega = \frac{\pi s^2\alpha_D}{4t_v t_H \eta}\left\{s - \ell\alpha_D\left(2 + \frac{1}{\eta}\right)\right\}$$

This is now an expression for the solid angle acceptance (and hence flux for a given $\Delta p/p$) of an optimally designed beam as a function of deflector and target parameters.

Separator Deflection

We can write[6] the maximum transverse momentum kick of a deflector $P_\perp$ as

$$P_\perp = \frac{\sqrt{ZPW}}{10}\,\ell_{att}\left(1 - e^{-\frac{\ell}{\ell_{att}}}\right)$$

where the units are such that

$P_\perp$ is transverse momentum kick in MeV/c

Z is series impedance in $(KV/cm)^2$/megawatts

PW is input power in megawatts

ℓ_{att} is attenuation length in meters

ℓ is the length of the deflector in meters

Table 1 is a list of Z and ℓ_{att} for our three deflector types. The parameters for the dielectric loaded structure are from Reference 2. The parameters of the iris loaded structure was scaled to X-band from the present BNL S-band structure assuming[3]

$$Z \propto \lambda^{-2}$$

and

$$\ell_{att} \propto \lambda^{3/2}$$

We assume the superconducting structure differs from the normal iris loaded structure only in that $\ell_{att} = \infty$. Figure 3 is a plot of $P_\perp$ as a function of ℓ at a power input of 1 megawatt. We note that there is no advantage of normal iris loaded structures of length greater than a few meters whereas for the other two structures the deflection is still approximately proportional to length in this region.

We may now compute the horizontal and vertical angular acceptance of these structures (α_H and α_V) as a function of length assuming a deflection equal to the natural angular divergence of the beam in the first deflector ($\eta = 1$) and an optimally filled structure. Here we also assume an incident momentum of 100-GeV/c and a power input of 1 megawatt. We also assume a target of transverse dimensions 1 mm x 1 mm ($t_V = t_H =$ 0.5 mm). Figure 4 is a plot of α_V and α_H for the three deflector types. Note α_H is independent of deflector type. We can also plot the solid angle acceptance of the three beams using each of these deflectors. This is done in Figure 5.

It should be noted that this comparison does the superconducting deflectors an injustice. We have assumed that we

would operate a superconducting deflector in the same manner as a normal structure. This need not be the case; the needed deflection can be achieved with much less power by either of the following techniques. Firstly, the structure can be operated as a resonant ring; here the output power of the traveling wave is returned back to the entrance of the deflector and additional power is added through a directional coupler. Secondly, one can operate the structure in a standing wave mode. Both of these would require sources much less than the megawatt of power (less than 100 watts) we have been discussing.

Design Procedures

Present RF separated beams are designed to operate with deflection angles of approximately 1 mr. Because of the greatly increased forward production of secondary particles expected at NAL energies we will still expect very substantial numbers of secondaries even with small beam angular acceptances which, in turn, imply that smaller angular deflections can be used. We believe that at NAL energies the size of the angular deflectio can be reduced by up to a factor of five with no appreciable loss of beam purity.

Referring to Figure 3 we see that if we wish to design a beam which will operate at 100-GeV/c, we then require a transve momentum deflection of at least 20 MeV/c. We see that this can be achieved by a single iris loaded superconducting deflecto of approximately 2.75 meters in length. It cannot be achieved by either an iris loaded normal deflector or by a dielectric loaded

deflector of reasonable length. Now having fixed the length of the deflector, we can refer to Figure 4 for the vertical and horizontal angular acceptance of the beam, and to Figure 5 for the solid angle acceptance of the beam. We see in Figure 5 that for a 2.75 meter isis loaded superconducting structure, we have a solid angle acceptance of about 19.4 μsr for an optimally designed beam. This is an extremely large possible solid angle for an RF beam design at NAL, and should be compared with 4 μsr of the beam in Reference 5. With the long duty cycle inherent in a superconducting structure, such a beam would clearly have wide application for both bubble chamber and counter use.

Power Sources at X-band

The highest power X-band klystron available commercially ("off the shelf") is the Varian VA-949 which is capable of providing 250 KW of CW power in the frequency range 7.1 - 8.5 GHz. The price of this tube is about $70,000. Varian has produced an experimental tube capable of 1 megawatt CW power. Although additional development to make a production item of this tube is still needed, delivery could be made in about one year. The cost for the first tube, including development, would be about $250,000. Additional tubes would be less expensive. It does not appear that running these tubes in a pulsed mode would increase their peak power capability significantly - perhaps only by a factor of two. Clearly superconducting structures which would have considerably lower power demands become very attractive from a power cost viewpoint.

Hughes Aircraft has a proposal to construct a 3 MW X-band TWT. This device is capable of at 50 μsec pulse and duty cycle of about 0.2%. The development time is estimated at one year and a cost of $200,000. The first tube would probably be sold for about $35,000. This might be a way of producing an effective bubble chamber beam.

Discussion

We must face the possibility that superconducting X-band structures will not be available in the early stages of our experimental program. What alternatives do we have then? Referring back to Figure 3, we see that a normal iris loaded structure of approximately 1.25 meters in length would provide a transverse momentum kick of 5 MeV/c. Thus 4 such structures mounted in series and driven by separate 1 megawatt power sources would give us the required transverse momentum deflection and have a total length of about 5 meters. For an optimally designed optical system this corresponds to a solid angle acceptance at the target of 6 μsr. This is still a beam of very substantial flux. It will not have the large duty cycle required by counter experiments, since the removal of 1 megawatt of RF power from each of these deflectors is a formidable one except for very short duty cycles. The RF power costs for such a scheme would probably be prohibitive however. Superconducting RF deflectors at X-band present the best solution to this problem

If superconducting X-band deflectors were not available at an early date there does exist the possibility of using S-band deflectors (superconducting if possible) and run the beam

at about 50 GeV/c. Separated pion and antiproton beams could be achieved over a much wider momentum region. Even the present BNL deflectors would be suitable for a bubble chamber beam if their pulse width would be increased to about 20 μsec which is the time required for single turn extraction.

Foelsche[7] has considered a normal temperature X-band iris loaded deflector for a low energy counter separated beam. He achieved more reasonable rf power consumption by breaking each of the deflectors up into about ten equal pieces and powering them separately. This is a cumbersome technique which one would only consider if superconducting structures were not available. Furthermore, it would only have applicability to lower energy beam in which purity was not of utmost importance.

The merits of dielectric loaded structures have not yet been completely evaluated. Certainly the device presented in Reference 2 cannot compete with the performance of a superconducting structure when used as a point deflector because of its small acceptance. If its acceptance could be increased (aperture increased and/or length decreased for a given deflection) or if a suitable strong focusing channel surrounding the structure could be designed, it might compete more favorably with a superconducting structure.

References:

1. J. W. Dawson and R. L. Kustom, "A Single Section Traveling Wave Particle Separator," JWD/RLK-1, Argonne National Laboratory.

R. L. Kustom, C. T. M. Chang, and J. W. Dawson, "Propagating and Transverse Deflecting Modes in a Dielectric Loaded Rectangular Waveguide," Argonne National Laboratory.

C. T. M. Chang, J. W. Dawson, and R. L. Kustom, "A Dielectric Loaded Slow Wave Structure for Separation of Relativistic Particles."

2. J. Sandweiss, "Use of Dielectric Loaded Waveguides for RF Particle Separation at NAL," SS-105, 1969.

3. H. Foelsche, "A Normal RF Separator with 33% Duty Cycle," SS-13, 1969, Volume 1, p. 119.

4. H. W. J. Foelsche, H. Hahn, H. J. Halama, J. Lach, T. Ludlam, and J. Sandweiss, "Radiofrequency Separated Beam at the AGS," Review of Scientific Instruments 38 879, 1969.

5. J. Lach, "200 BeV Accelerator," Studies on Experimental Use, Volume 1, p. 190, 1965.

6. P. Bernard, H. Lengeler, and V. Vaghin, CERN 68-30, 1968.

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TABLE 1

(All Structures at 10 GHz)

	Z	ℓ_{att}
Normal iris loaded structure	465 $\left(\frac{KV}{cm}\right)^2$/MW	0.925 m
Superconducting iris loaded structure	465	∞
Dielectric loaded structure	20	62

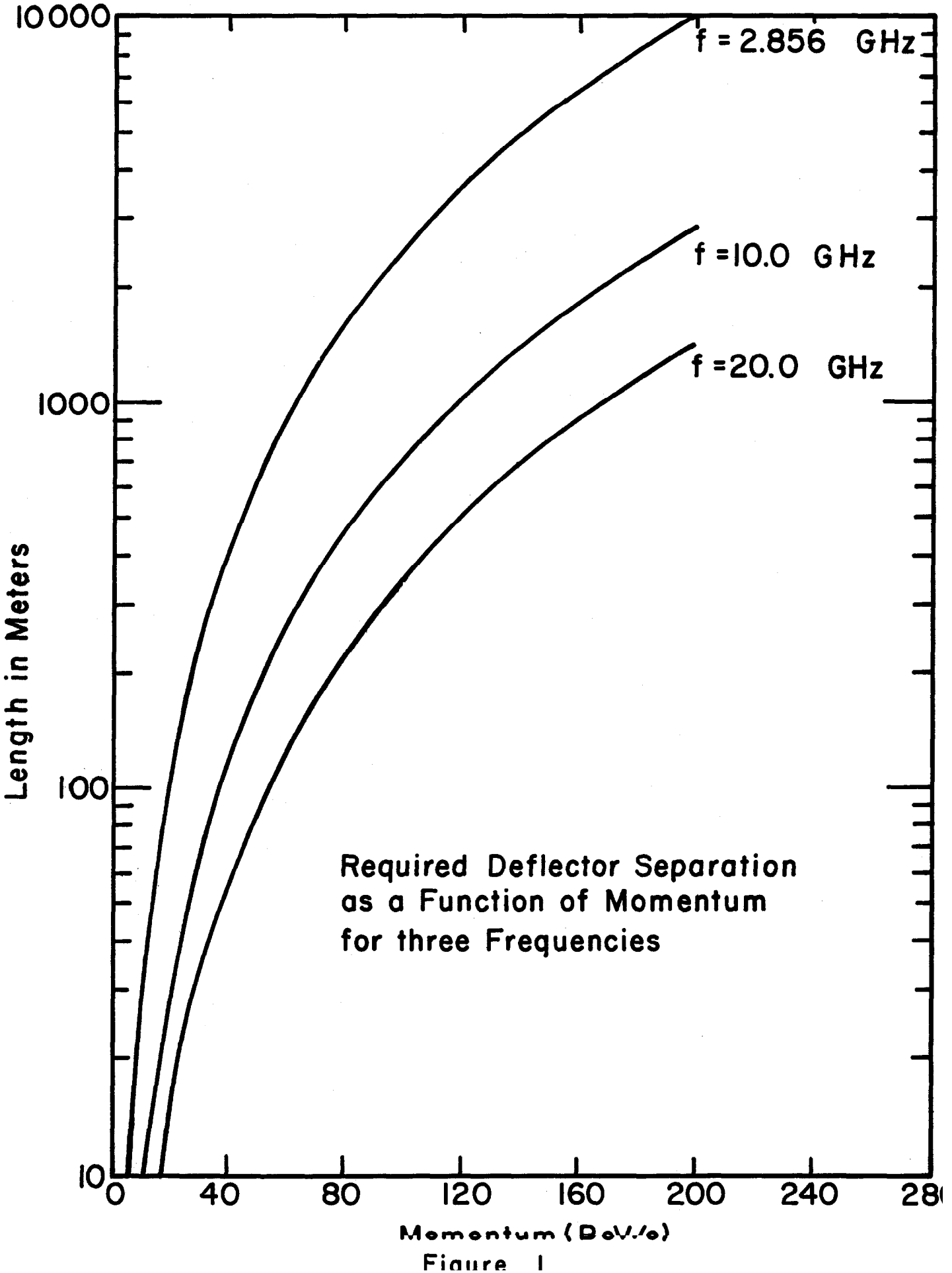

10000
1000
100
10
Length in Meters
f = 2.856 GHz
f =10.0 GHz
f =20.0 GHz
Required Deflector Separation
as a Function of Momentum
for three Frequencies
0
40
80
120
160
200
240
Momentum (BeV/c)

Figure 1

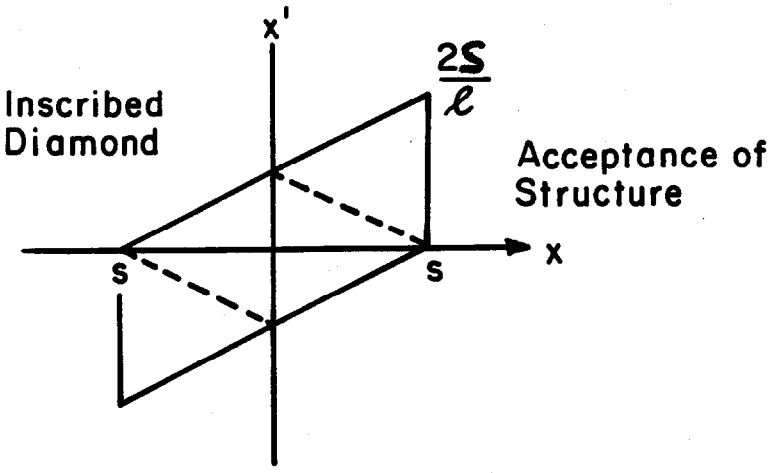


Figure 2a

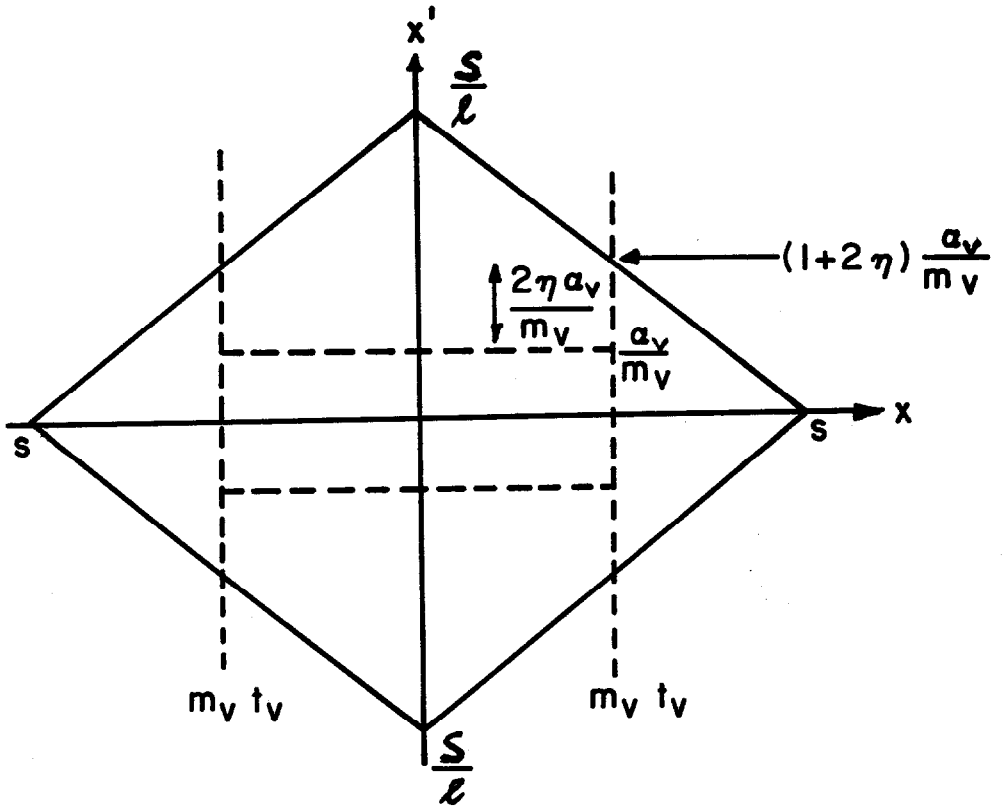


Figure 2b

FIGURE 3

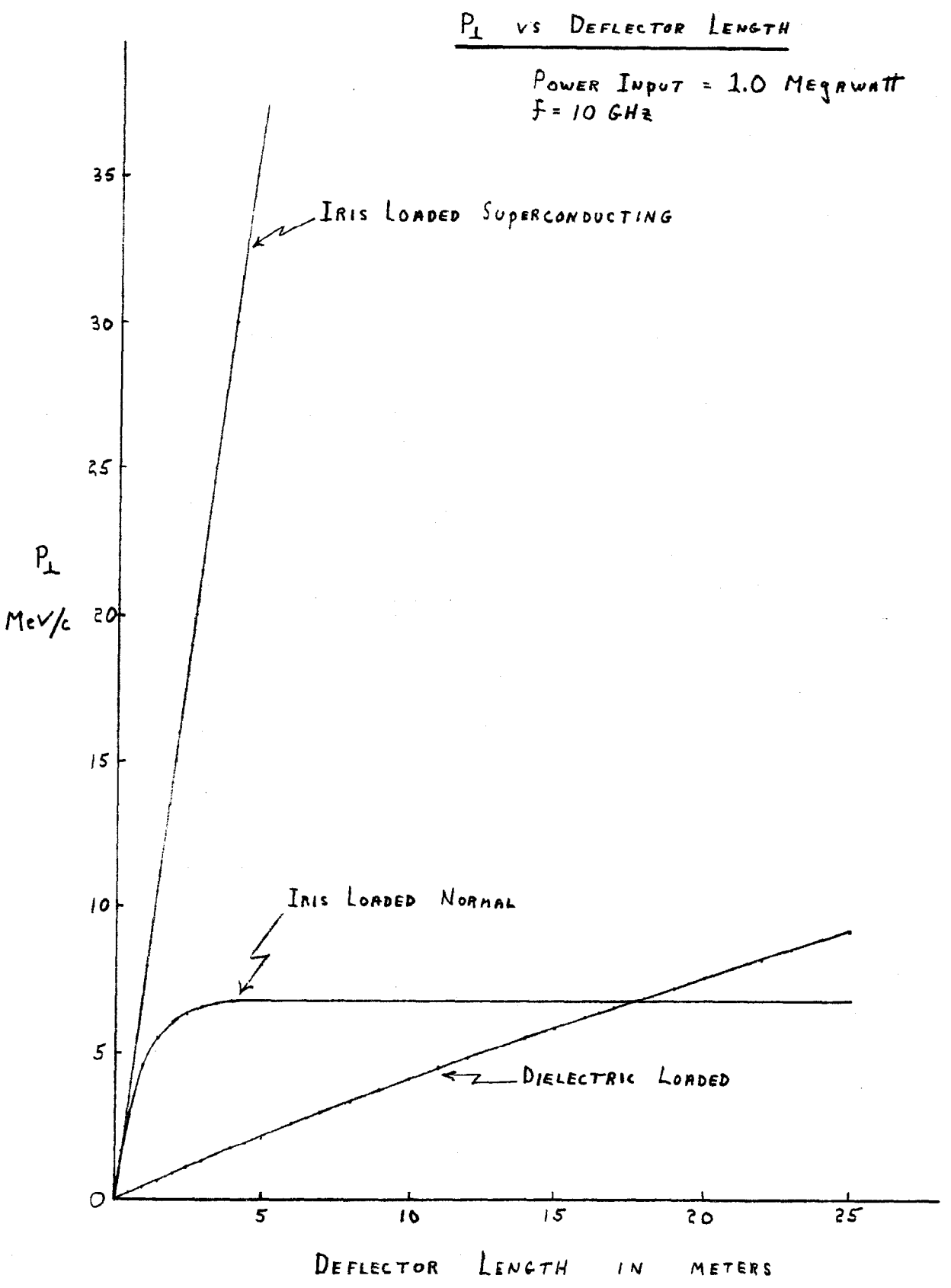

$P_\perp$ vs Deflector Length
Power Input = 1.0 Megawatt
F = 10 GHz
Iris Loaded Superconducting
Iris Loaded Normal
Dielectric Loaded
$P_\perp$
MeV/c
0
5
10
15
20
25
30
35
5
10
15
20
25
Deflector Length in meters

FIGURE 4

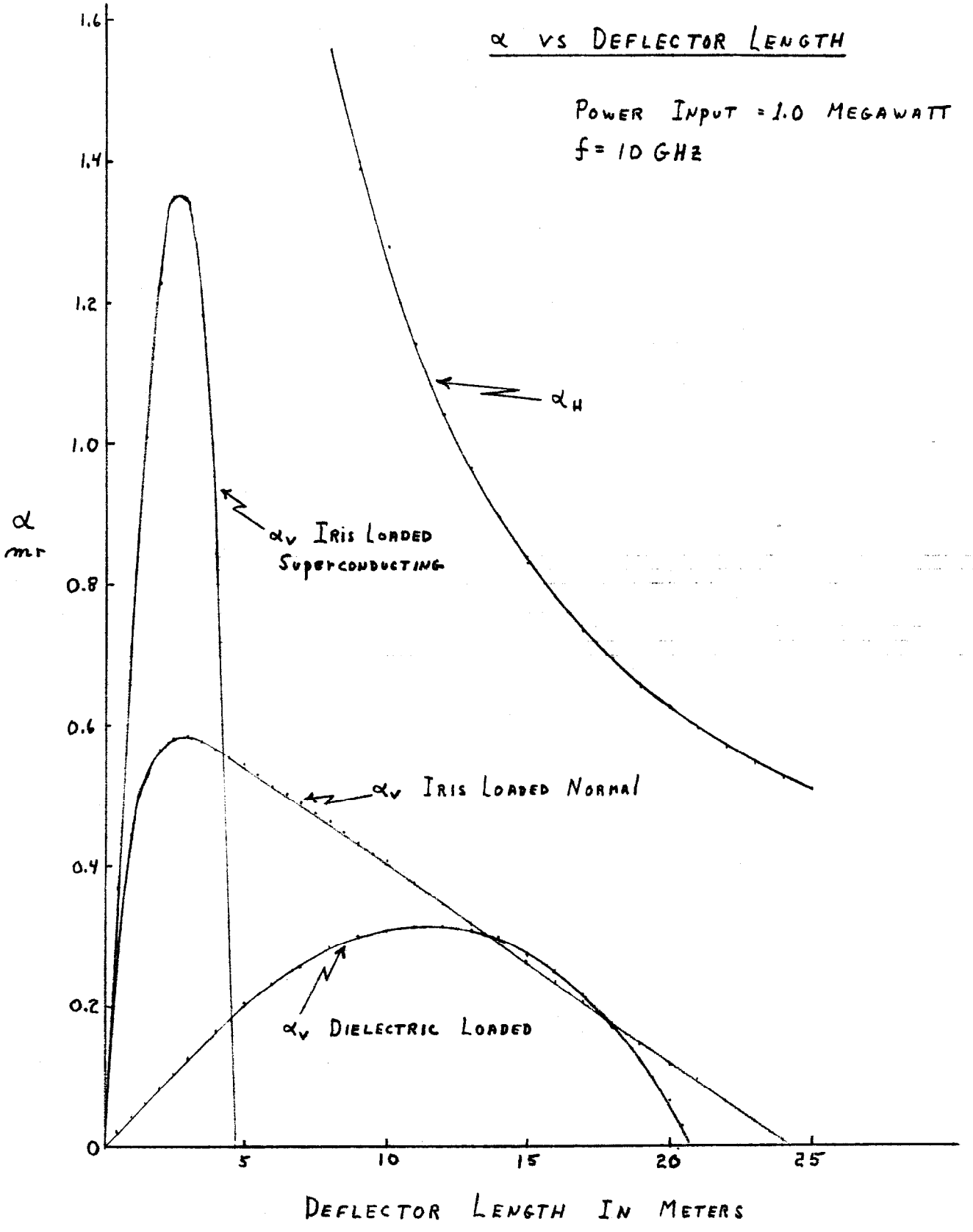
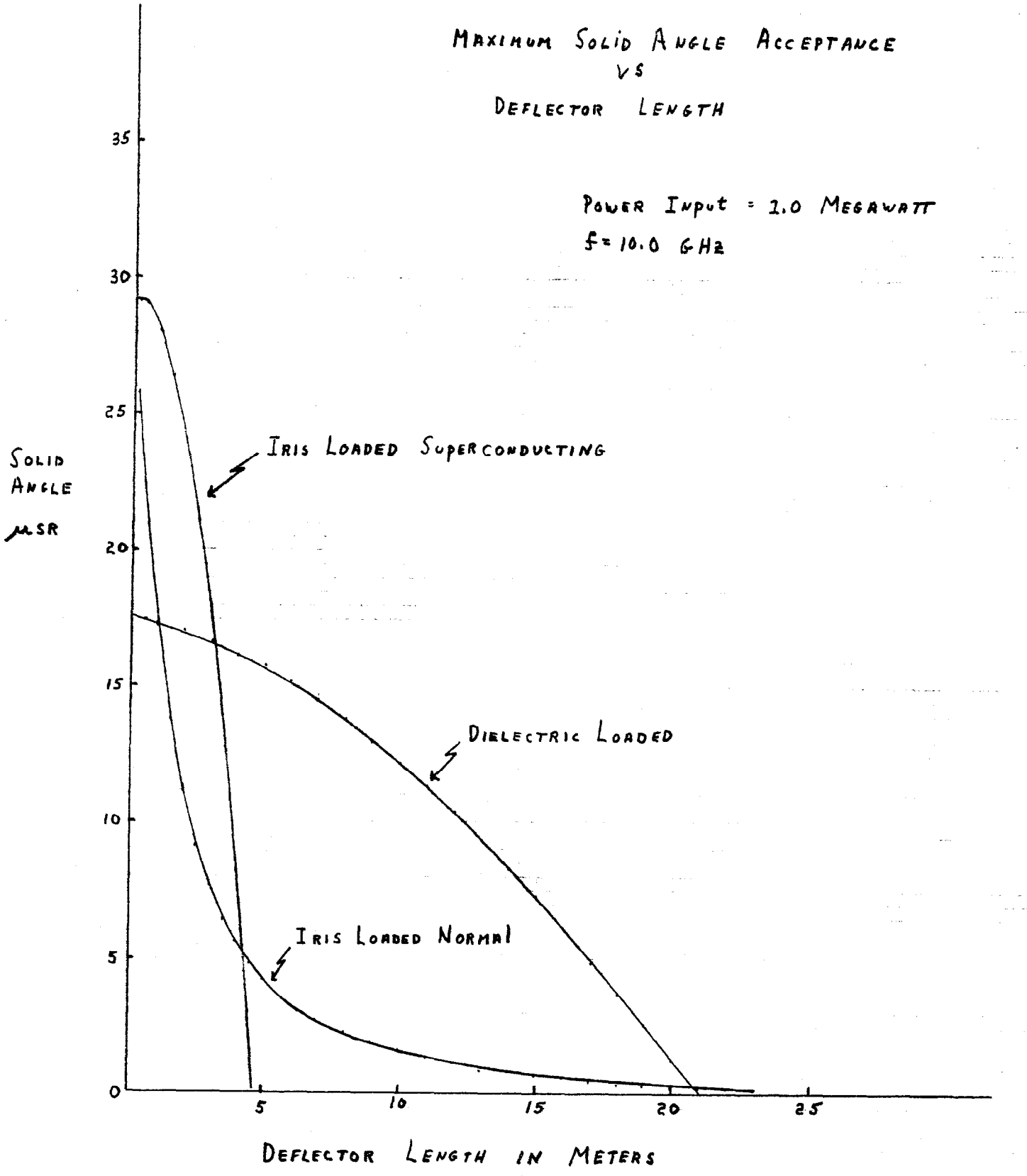

α vs Deflector Length
Power Input = 1.0 Megawatt
f = 10 GHz
α mr
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
α_H
α_V Iris Loaded Superconducting
α_V Iris Loaded Normal
α_V Dielectric Loaded
5
10
15
20
25
Deflector Length In Meters

FIGURE 5


MAXIMUM SOLID ANGLE ACCEPTANCE
VS
DEFLECTOR LENGTH
POWER INPUT = 1.0 MEGAWATT
f = 10.0 GHz
SOLID ANGLE
μSR
IRIS LOADED SUPERCONDUCTING
DIELECTRIC LOADED
IRIS LOADED NORMAL
0
5
10
15
20
25
30
35
DEFLECTOR LENGTH IN METERS